Evaluation of the thermal performance of an innovative pre-fabricated natural plant-fibre building system.

Dr. Andy Shea, Dr. Katharine Wall, and Prof. Pete Walker

Abstract

Energy efficient new and retrofit building construction relies heavily on the use of thermal insulation. A focus on the environmental performance of current construction materials with regards to both embodied energy and energy in-use has resulted in a growing interest in the use of natural fibre insulation materials. The results of Heat Flow Meter thermal conductivity tests on a range of straw samples of different densities are presented. The innovative use of straw in the development of a prefabricated straw-bale panel and the results of Guarded Hot Box testing are presented. In common with most building materials, there is a degree of uncertainty in the thermal conductivity due to the influences of temperature, moisture content and density, however, from evaluation of a range of literature and experimental data, a value of 0.064 W/m·K is proposed as representative design value for straw-bales at the densities used in building construction. Computer simulation and experimental testing suggest that the overall heat transfer coefficient (U-value) for the complete prefabricated panel is approximately 0.178 $W/m^2 \cdot K$. This paper also briefly discusses the use of this innovative unit in a highly-instrumented test building constructed at the University of Bath.

Practical application:

Knowledge of the thermal properties of building materials is necessary for evaluation of energy performance of the building envelope and appraisal of retrofit fabric improvements. The presentation of robust data for the thermal properties of straw will be of interest to designers developing projects employing this natural fibre insulation material.

BRE Centre for Innovative Construction Materials,

Department of Architecture and Civil Engineering,

University of Bath,

Bath, BA2 7AY.

a.shea@bath.ac.uk

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Introduction

Thermal conductivity is the rate of steady-state heat flow (W) through a unit area of 1 m thick homogeneous material in a direction perpendicular to isothermal planes, driven by unit (1 K) temperature difference across the material sample[1]. Thermal conductivity, λ (W/m·K), is a measure of the effectiveness of a material in conducting heat and the thickness of the material divided by its conductivity gives the thermal resistance (m^2·K/W). The U-value, which is the overall heat transfer coefficient, is defined as the reciprocal of the sum of all the thermal resistances of the layers of the building element including resistance due to a film of air at the inner and outer surfaces. U-values are useful for comparing the thermal performance of building elements e.g. walls, windows, roofs etc. U-values form the basis of many regulatory frameworks aimed at conserving the use of fuel and power in buildings and are a fundamental part of EU members' methodologies for demonstrating compliance with the Energy Performance of Buildings Directive[2]. Uncertainty in the thermal conductivity of the individual construction materials will impact the overall heat transfer coefficient and any subsequent prediction of building energy use. Furthermore, as the insulation generally represents the greatest thermal resistance of any layer in a building element, uncertainty in the thermal conductivity of the insulation material will result in proportionately greater impact on the results of building energy performance modelling.

The apparent, i.e. measured, thermal conductivity of building materials is a function of density, temperature, moisture content, and age. Additionally, for easily compressible materials, such as straw and mineral wool, the effects of pressure influence conductivity and, for example, when in service as a cavity fill can 'slump', which leads to greatly increased heat loss due to convection in the cavity space. To avoid slump in the proposed prefabricated straw bale building system, which is constructed of straw bales contained within an engineered timber frame and rendered on both sides, a high density straw bale is required. Clearly, the air trapped within the voids of the straw material has a much lower thermal conductivity than the solid fibres thus compressing the material to achieve a higher density greatly reduces the number of voids, thereby increasing the thermal conductivity of the material as a whole. Accordingly, to achieve a suitable balance of density and thermal conductivity a series of straw bale test specimens were evaluated using a Heat Flow Meter. The results of these tests are presented and discussed here along with a number of thermal performance tests including Hot Box Testing of a complete rendered straw bale panel.

Straw as a material for building thermal insulation

Insulation materials can broadly be grouped into three categories, inorganic, organic and metallic[3]. The primary purpose in each case is to reduce heat transfer, buffer moisture, and store heat within the building envelope. In general terms insulation materials work by trapping air within their structure and the low rate of air conduction minimises the transfer of heat. At present inorganic insulation materials dominate the building industry, although interest in the use of natural fibre insulation products is steadily increasing[4]. This is due, in part, to the requirement to find alternatives to the current materials many of which have negative impacts on the environment and health. Low environmental impact materials, such as natural fibre insulation, can have the advantage of reduced greenhouse gas emissions from sourcing, production and transportation, plus the potential to out perform 'standard' products in terms of health, acoustic and thermal benefits[5].

Straw is a renewable biomass and is readily available, in cereal producing regions, as a co-product of the agricultural sector. Data for 2000-2009 show that the UK average annual wheat crop yield is approximately 7.8 t/ha and average yields have increased steadily since the 1970s[6, 7]. Recoverable cereal straw biomass on UK farms typically ranges from 2.75 – 4 t/ha. The energy input to those operations dedicated specifically to the baling of the straw have been calculated by Tsatsarelis[8] as 2970 MJ/ha corresponding to an energy input of 0.75 to 1.09 MJ/kg, which is considerably less than the embodied energy of many other forms of insulation.

The measurement of the thermal conductivity of building materials can be determined through guarded hot plate or heat flow meter hot plate methods and BS EN ISO 8990[9] and ISO 8301[10] describe the appropriate test methodologies and equipment specification. Edge losses and changes in temperature across the plates of the test equipment will influence the measured conductivity. However, test methods and the equipment used are capable of achieving accurate, repeatable results and uncertainty can largely be attributed to changes in the material properties such as density, moisture content, porosity, fibre size and orientation. Beck et al.[11] and the association of straw bale construction Germany, Fachverband Strohballenbau (FASBA)[12], studied the effect of moisture content on thermal conductivity and reported a 20% increase in thermal conductivity from its dry state to a state of equilibrium with an environment of 23°C and 80% RH. Ashour[13] reported similar results for both wheat and barley straw and also that increasing temperature has a significant effect on thermal conductivity. Ashour[13] performed conductivity tests on five straw bales ranging from 82 kg/m^3 to 138 kg/m^3 and at three mean temperatures of 10.3°C, 20.7°C and 34.2°C. Apparent thermal conductivity increased by a factor of between 2.3 to 2.8 from 10.3°C to 20.7°C, with a further rise of, typically, 10% from 20.7°C to 34.2°C.

FASBA[12] and Munch-Andersen & Andersen[14] investigated the effect of the orientation of the straw in relation to thermal conductivity and the overall thermal transmittance of straw bale wall construction. Conventionally, straw bales are referred to as 'flat' when lying on their largest face[15] and heat flow is perpendicular to the straw strand direction. Correspondingly, bales laid 'on-edge' experience heat flow parallel to the straw strand direction. However, an identifiable straw orientation depends on the type of baler and the size of the bale. Straw bales come in various sizes but those most commonly used for building are typically 'two-string' measuring approximately 350 mm high x 450 mm wide x 910 – 960 mm long or 'three-string' 420 mm high x 600 mm wide x 1060 - 1190 mm long. McCabe[16] undertook tests conforming to the American ASTM C177-85 standard[17] on large 'three-string' bales. The bales tested consisted of wheat straw with an average density of 134 kg/m^3. Laid flat, with heat flow perceived to be perpendicular to the straw orientation, thermal conductivity was measured as 0.0457 W/m·K, and when laid on-edge this increased to 0.0606 W/m·K. Munch-Andersen and Andersen[14] tested 150 mm thick sections of a half-bale in flat and on-edge orientations and found, as McCabe[16], that the resistance to heat flow was greater for bales laid on-edge i.e. where heat flow is perpendicular to the straw direction. The effect of bale density and straw orientation can both be observed from the tests conducted by Munch-Andersen and Andersen[14]. At the lower density of 75 kg/m^3 thermal conductivities of 0.052 W/m·K (perpendicular) and 0.057 W/m·K (parallel) were observed. With density increased to 90 kg/m^3 these figures were 0.056 W/m·K (perpendicular) and 0.060 W/m·K (parallel). Thus for the lower density case a change of orientation from perpendicular to parallel heat flow resulted in a 9% increase in thermal conductivity, whilst for the higher density sample the increase was 7%. Increasing density resulted in increased conductivity of 7% and 5% for the perpendicular and parallel cases, respectively. FASBA[12] carried out a series of tests to establish the relationship between thermal conductivity and straw orientation. The tests were conducted using a guarded hot plate method as per BS EN 12667 standard[18] and the specimens were assembled such that each individual length of straw was aligned either perpendicular or parallel to the heat flow. Measurements by FASBA[12] determined that the thermal conductivity when straw was aligned parallel to heat flow could be as much as 50% greater than the perpendicular to heat flow condition.

Methods

Heat Flow Meter thermal conductivity tests

To establish the thermal conductivity of straw bales of different densities a selection six test specimens were tested at the British Board of Agrément (BBA) test facility at Garston, UK.

The straw bales sourced for production of the prefabricated wall panels and the conductivity test specimens were two-string bales. In these smaller bales straw appears to be randomly orientated (Figure1).

Figure 1 Cross-section through a two-string bale.

The test bales were prepared at the University of Bath to be tested using a FOX 800 Heat Flow Meter. The FOX800 unit at the BBA facility is modified by the addition of external side guards (Figure 2), which permits reliable measurement of samples up to 300 mm thick. The plates are 760mm x 760mm, the metering area is 305mm x 305mm, and the rig is calibrated to an Institute for Reference Materials and Measurements (IRMM) 440 reference standard[19]. To construct the test samples for thermal conductivity testing loose straw was added to a box and compressed using a hydraulic jack (Figure 3).

Figure 2 Lasercomp FOX800 Heat Flow Meter with heated edge guard.

Figure 3 Equipment used to create test bales at the University of Bath.

Samples were then tied and wrapped in a vapour permeable membrane. Test samples were moved to the BBA test facility and conditioned in a temperature and humidity controlled space at 23°C and 50% RH. At the time of testing the densities of the six samples were 63, 76, 85, 107, 114, and 123 kg/m^3. The specimens were tested using the heat flow meter method of ISO 8301: 1991[10] and BS EN 12667:2001[18]. Subsequent conductivity testing was undertaken using a smaller FOX600 Heat Flow Meter at the University of Bath Environmental Engineering Laboratory to investigate the influence of temperature on apparent thermal conductivity. A further set of six wheat straw specimens measuring 600 mm x 600 mm x nominally 150 mm were prepared. The samples had densities ranging from 67 kg/m^3 to 112 kg/m^3 and were tested at mean temperatures of 10°C and 30°C.

The BaleHaus

The prefabricated panels are known as 'ModCell' (Modular Cellulose) panels and are typically constructed of a 100 mm thick pre-cut engineered glue- or cross-laminated timber to a frame size of 3.19 m wide x 2.66 m high and 0.49 m thick. The solid frames are in-filled with 18 complete wheat straw bales and six half bales in alternate layers of three whole bales and two whole bales with two half bales to create a coursed construction. The bales are pinned together every other layer with timber dowel and stainless steel reinforcement is used as corner bracing and as vertical ties. The panels are spray rendered with formulated lime in three layers before delivery to site. There is the equivalent of 21 bales within a complete panel. Panels made for the prototype house contain straw of a density of approximately 115 kg/m^3. The BaleHaus@Bath was built on the University of Bath campus to enable development of the panels for use in load-bearing mainstream housing construction. The panel construction and finished prototype house, BaleHaus @ Bath, is presented in figure 4. Details of the 'flying factory' and construction of the BaleHaus are presented in[20].

Figure 4 ModCell panel under construction in a 'flying factory' (left) and the completed prototype house at the University of Bath campus (right).

Thermal transmittance testing of the prefabricated 'ModCell' panel.

The thermal transmittance of a pre-fabricated straw bale panel was also tested at BBA[21] to establish the overall thermal transmittance co-efficient (U-value) of the panel. A specimen panel of 3.4 m high, 3.5 m wide and 0.49 m thick was constructed in-situ. The panel was left for seven days before testing to enable the formulated lime render basecoat to develop an initial set. A Guarded Hot Box (Figure 5) was used to conduct the test. The Guarded Hot Box had a metering box aperture of 1.9 m high by 2.4 m wide. The guard chamber and cold box apertures were 2.8 m high by 3.3 m wide[21]. The vertically mounted panel was placed between the hot and cold boxes to allow heat flow to be in the horizontal plane. Type T thermocouples were attached to the surfaces of the panel and the difference in these temperatures and the ambient air temperatures used to calculate the thermal resistivity and the U-value of the panel. Testing was undertaken in accordance with BS EN ISO 8990: 1996[9].

Figure 5 Prefabricated ModCell panel and Guarded Hot Box facility at the BBA, Garston, UK.

Experimental results

Straw thermal conductivity

The results from the thermal conductivity tests on the straw specimens at different densities are shown in Table 1. Prior to testing, the specimens were conditioned in an environmental chamber at 23 ± 2°C, 50 ± 5% RH until a stable mass was achieved.

Table 1: thermal conductivity for a range of sample densities.

Density kg/m^3	Thermal conductivity W/(m·K)	Thermal resistance m^2·K/W	Mean temperature (°C)
63	0.0594 ± 2.5%	4.43 ± 2.5%	10.1
76.3	0.0621 ± 2.5%	4.45 ± 2.5%	10.1
87.4	0.0619 ± 2.5%	4.6 ± 2.5%	10.1
107	0.0642 ± 2.5%	4.42 ± 2.5%	10.1
114	0.0642 ± 2.5%	4.39 ± 2.5%	10.1
123	0.0636 ± 2.5%	4.41 ± 2.5%	10.1

The results show that the thermal conductivity of test specimens varied by only 0.0048 W/m·K across the six specimens. There is a general trend over the experimental range for thermal conductivity to increase with density. However, thermal conductivity for the wheat straw bales was less sensitive to increasing density than originally anticipated.

Figure 6 presents the results of conductivity versus density for two mean temperatures. On average the increase in mean temperature from 10°C to 30°C increases apparent thermal conductivity by 15%.

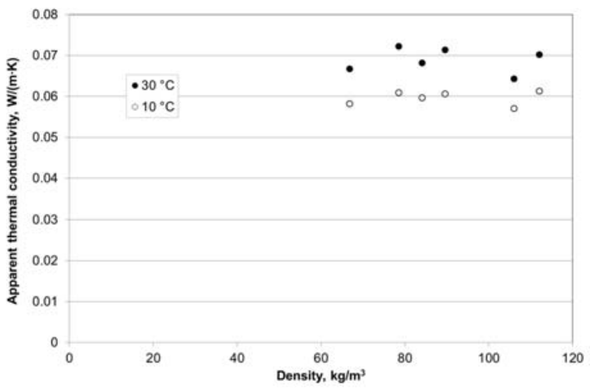

Figure 6 Thermal conductivity versus density at 10°C and 30°C.

Thermal transmittance of a prefabricated straw bale panel.

The Guarded Hot Box test duration was approximately 137 hours in total, which comprised a period of 106 hours required to reach steady-state conditions followed by a 31 hour period of stability. The laboratory temperature during this period was 21°C to 23°C. Within the box, the mean air temperatures either side of the panel were measured as 21.8°C and 0.1°C. On the cold surface an air velocity of 3 m/s was maintained and all surfaces ‘seen’ by the test specimen were matt black. Warm side surface resistance was measured as 0.132 m^2·K/W and cold side as 0.045 m^2K/W. The results from the thermal transmittance test on the prefabricated straw bale panel gave a measured thermal transmittance of 0.190 ± 0.015 W/m^2·K. The test was repeated at a laboratory temperature of 15°C to examine the effect of edge losses. This yielded a U-value of 0.189 W/m^2·K, which is not considered significant and is within the overall estimate of measurement uncertainty[21].

Inspection of the completed BaleHaus.

An infrared thermographic survey was undertaken on the prototype straw bale house to identify any thermal anomalies, thermal bridging, air infiltration, or other weaknesses in the building fabric. Current building regulations Approved Document Part L[22], which relates to the conservation of fuel and power, provides guidance with regards to the quality of construction. The Approved Document[22] indicates that the fabric of the building should be constructed to a reasonable quality to ensure that the insulation is continuous over the whole building envelope. Additionally, air permeability of the building envelope should be no worse than 10 m^3/hr per m^2 at a pressure difference of 50 Pa. Externally, the survey showed no sign of thermal bridging or building defects. Internally the panels showed even temperatures across their surfaces (Figure 7). Infiltration can be identified around the edges of the panels due to the small gaps around the render rather than any inconsistency with the straw in-fill. For the duration of the test, the building was heated to 20°C and under negative pressure. An air permeability test for the completed BaleHaus was undertaken to ATTMA TS1[23] and BS EN 13829[24] standards and a value of 0.86 m^3/hr.m^2 envelope was measured, which is less than 1/10th that permitted by current building regulations.

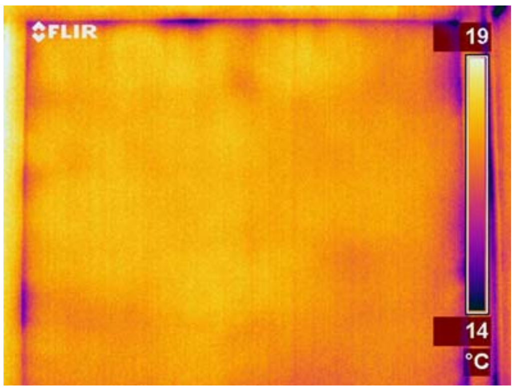

Figure 7 Thermal image of panel in the prototype prefabricated straw bale house.

Discussion

A summary of thermal tests performed in North America to 2001 has been made by Stone[25]. In France, the Centre d'Expertise du Bâtiment et des Travaux Publics (CEBTP)[26] tested straw bale walls with a 20 mm lime render and measured a U-value of 0.25 W/m^2·K for a 360 mm thick wall. Stone[25] reported U-values for straw bale walls ranging from 0.334 W/m^2·K for a 457 mm wall to 0.087 W/m^2·K for a 584mm wall. Watts et al.[27] performed in-situ testing of a straw bale walled house in Canada using hot plates in which a series of three tests resulted in an average U-value of 0.200 W/m^2·K for a wall of approximately 467 mm thick. In the US, tests conducted at the Oak Ridge National Laboratory[25] using two-string bales at 13% moisture content and plastered on both sides produced a U-value of 0.206 W/m^2·K for a wall thickness of approximately 483 mm. The California Energy Commission officially regards a plastered straw bale wall to have an R-value of 30 ft^2·°F h/Btu, equal to R 5.28 m^2·K/W or 0.189 W/m·^{2}K, remarkably similar to the measured U-value of 0.190 W/m^2·K for the ModCell prefabricated unit. Prior to the laboratory testing of the ModCell unit and series of 3-D simulations of the thermal performance were performed[28]. The analysis was undertaken using the 3-D steady state heat transfer software TRISCO. A number of assumptions were made when undertaking these simulations, which are presented below:

- 1 W/m·K – thermal conductivity of the lime render
- 0.13 W/m·K – Timber (frame and dowels)
- 17 W/m·K – Stainless steel (reinforcement)
- 50 W/m·K – Stainless steel (screws)
- 30 mm – render on each face
- 430 mm – thickness of straw bales

Cold-side environmental temperature, T_e, was taken as 0°C and warm-side environmental temperature, T_i, as 20°C. External (R_{se}) and internal (R_{si}) surface resistances were 0.04 m^2·K/W and 0.13 m^2·K/W, respectively, corresponding to standard values presented in BS EN 6946[29]. Straw conductivity values from published literature[14,16] plus a higher value were used to evaluate typical and worse-case conductivity and its impact on the overall thermal transmittance. Additionally, a simple 1-D U-value calculation, ignoring the effects of steel fixings, reinforcement, and the timber frame and dowels was performed for the same range of straw conductivity values. The results of the 3-D simulations and 1-D calculations are presented in Table 2.

Table 2: 3-D simulation and 1-D calculation of panel U-values for a range of straw conductivities.

Thermal conductivity of straw	W/m·K	0.045	0.05	0.086
1-D simple calculation	W/m^{2}K	0.102	0.113	0.191
3-D TRISCO model	W/m^{2}K	0.125	0.134	0.202
Percentage increase from 1-D to 3-D	%	22.5	18.6	5.8

Comparing the results presented in Table 2 with the Guarded Hot Box test result (0.190 W/m^2·K) would indicate that the straw within the test panel had a thermal conductivity within the range 0.072 W/m·K to 0.088 W/m·K. Of course, the thermal conductivities for other materials will also vary and both the thickness and thermal properties of the lime render vary due to application technique, unevenness is the substrate material and the formulation of the lime; all of which will have some small (<1%) influence on the overall thermal transmittance of a typical ModCell, or similarly constructed, panel. As edge losses from the Guarded Hot Box test have been demonstrated to be small (0.001 W/m^2·K) and the test mean temperature is the same as that used for the Heat Flow Meter thermal conductivity tests, the most likely source of uncertainty is a result of differences in moisture content.

CEBTP[26] tested straw bales at different RH levels. The thermal conductivity was found to vary between 0.064 W/m·K at 0%

RH and 0.072W/m·K at 90% RH. FASBA[12] reported a 20% increase in thermal conductivity from dry state to 23°C and 80% RH. Conductivity test results from this study, from samples which were conditioned to 23°C and 50% RH prior to testing, are presented in Figure 8 with FASBA[12] data for samples in a dry state and CEBTP[26] data at 0%, 50%, and 90% RH. It should be noted that the increase in density in the CEBTP tests is due to the increased mass of water and not, as is the case in the other tests, a result of increased compression of the straw.

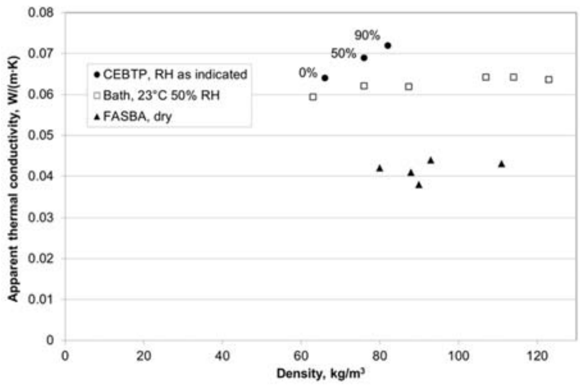

Figure 8 Thermal conductivity versus density for a range of straw samples in dry and humid states.

At the same relative humidity and density the mean test result for the CEBTP[26] data is 11% higher than the Bath data, which, given overall uncertainty in thermo-physical properties of the straw samples, is reassuringly similar. The FASBA[12] in a dry state and with straw strands aligned normal to the direction of heat flow represents the lower limit of thermal conductivity. The Bath conductivity data, which more closely resembles 'typical' state conditions, are, on average, 48% higher.

Wheat straw bales for use in the manufacture of the ModCell prefabricated straw bale panels have a density of between 110-120 kg/m^3 and are compacted further during panel fabrication. Whilst the level of compaction will affect the apparent thermal conductivity, across the range of densities used for building construction the measured thermal conductivities were much less sensitive to changes in bale density than expected. The insensitivity to density variation is beneficial for panel construction, allowing bales to be compacted in preparation for rendering without significant detriment to insulation performance. Additionally, increased density provides a better substrate for render application, and denser bales are likely to offer improved fire resistance.

Conclusions

In general the previous test results from bales laid flat, with straw perceived to be orientated perpendicular to the heat flow, yield lower thermal conductivity values than those laid on-edge, with the heat flow parallel to the straw orientation. This is particularly evident in the tests conducted by FASBA[12] where the straw was artificially aligned to ensure that every strand was either parallel or perpendicular to the heat flow, depending on the test. The results from Munch-Andersen and Andersen[14] show much smaller differences between 'flat' and 'on-edge' bales. A specific straw orientation appears difficult to discern in the smaller 'two-string' bales, which is the size used in the construction of the ModCell panels.

Relative humidity and temperature do have a significant impact on the measured thermal conductivity. The literature[12, 26] suggests that between the dry state and equilibrium with an environment at 23°C and 80% RH the apparent thermal conductivity increases between 12% - 20%. An increase in mean temperature from 10° to 30°C results in a 15% increase in the measured thermal conductivity, although other sources[13] have reported much greater increases.

A least squares regression model for the determination of apparent thermal conductivity as a function of density results in a thermal conductivity value of 0.064 W/m·K at 120 kg/m^3, which is representative of typical straw density for a ModCell panel. This equates to a U-value of 0.178 W/m^2·K, which is within the range of uncertainty for the Guarded Hot Box test result, although for design purposes the mean test value of 0.19 $W/m^2 \cdot K$ is proposed.

This paper has highlighted the sources of uncertainty in the apparent thermal conductivity of straw for use in building applications and proposes, on the basis of laboratory test results and computer simulation, a typical value for thermal conductivity and overall thermal transmittance coefficient. These values will be of interest to designers and researchers wishing to evaluate the thermal performance for projects employing this natural fibre insulation material. The data permit comparison with building regulations performance standards for opaque building elements, conventional wall assemblies, and building energy performance through, for example, simple degree-day or similar methods. Furthermore, thermal imaging and air pressure testing of a full-scale test building, the BaleHaus@Bath, have demonstrated continuity of insulation and very low levels of air permeability, in addition to the inherently low embodied energy associated with the use of natural fibre insulation materials. Moisture content was not measured as part of this study, however, the determination of moisture sorption isotherms for straw forms part of current work by the authors and colleagues at the BRE Centre for Innovative Construction Materials.

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